Does VPP exist in lateral balancing?

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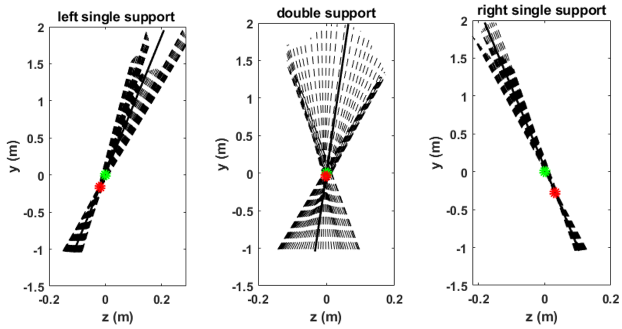
1 INTRODUCTION

As most of the body weight is located in the upper body, and due to the small supporting base, human walking is inherently unstable and as a result, balance or posture control is necessary for bipedal locomotion [1]. Using either inverted pendulum (IP) or virtual pendulum (VP) [2] model, one can describe balance control in human and bipedal robot locomotion. Maus et al. presented VP concept and the VPP (virtual pivot point) model for the postural balance during bipedal gait [2]. During walking, ground reaction forces (GRF) intersect at a point above the center of mass (CoM). This behavior can be predicted by a regular pendulum. It is shown in simulation, that using VP concept, can result in stable walking [3] [2]. In the controller which is based on VP, the relative angle between the upper body and the leg is used for balance control. It means that the controller can be implemented using the mechanical complaint element such as adjustable spring [3]. This is an advantage of the VPP-based control method for balancing compared to others which use upper body orientation with respect to ground [4]. So far, the VP concept has been used for balance control in the sagittal plane only. Due to the narrow width of the supporting base in the frontal plane, lateral balance control has more challenges compared to balance in the sagittal plane [5]. Furthermore, the pelvis as a segment perpendicular to legs and the upper body has a critical role in the frontal plane which is not addressed in the sagittal plane. In this study, we use the VPP concept to explain lateral balance for the first time.

2 METHODS

The VP concept has been observed in human walking and it can be useful for design and control of humanoid robots and assistive devices. For finding the location of VPP, we need a reference frame which is defined with respect to the human body. If the intersection of GRF vectors result in the creation of a focused point in the coordinate frame that represent upper body orientation, VPP concept can be used to analyze posture control [2]. Center of mass (CoM) of a rigid or segmented body is an optimal choice to be the origin for the reference frame addressing body posture. in this study, we used two different reference frames, one attached to the whole body CoM (WBCoM-centered) and the other, attached to the upper body CoM (UBCoM-centered). in both cases, y-axis is aligned with respect to pelvis angle.



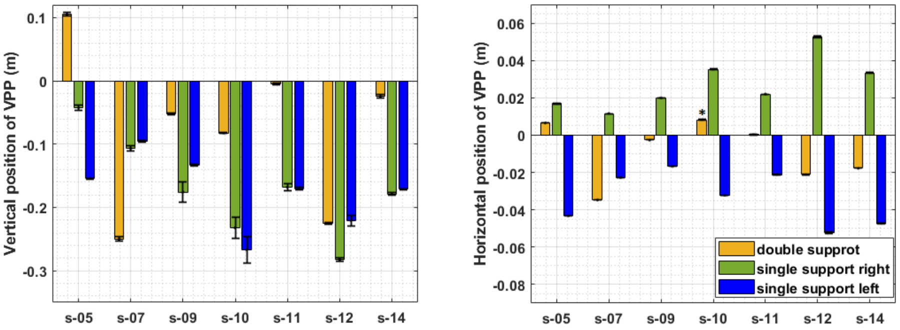
(a) (b) (c)

Figure 1: The VPP (red circle) in WBCoM-centered (green circle) coordinate frame aligned with trunk orientation. Dashed lines show the ground reaction forces from CoP.

We select pelvis orientation, for alignment of the reference frame, because the control of the pelvis motion is critical for the lateral balancing and trunk weight acts downward through the pelvis [5]. In this study, we use motion capture data from a group of seven human subjects walking at normal speed (1.45 ± 0.15 m/s), borrowed from [6].

3 RESULTS

To investigate the existence and cuality of VPP in the frontal plane, the ground reaction forces are illustrated in the body coordinate frame. In Fig. 1 GRF vectors are drawn from center of pressure (CoP) by dashed lines in the WBCoM-centered coordinate frame at free speed. This figure shows how clear GRF vectors intersect at a point. The graphs for UBCoM-centered system is similar to this (not shown). Fig. 2 shows mean and variance of VPP's location in the WBCoM-centered coordinate system at preferred speed. Our results show that for all subjects in single support phase (SS), VPP's vertical position in WBCoM-centered coordinate is below the center of mass. And for most of the subjects in double support phase (DS), VPP is placed below the center of mass. Moreover, these results are consistent with the slow speed condition (1.2 ± 0.1 m/s) as well. For all subjects in all phases and both free and slow speed conditions, VPP is located below the CoM for UBCoM-centered coordinate (not shown). However, the variance of VPP's vertical position in the case of UBCoM-centered coordinate is more than WBCoM-centered coordinate. Due to the space



(a)

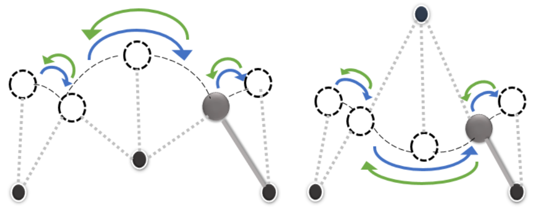
(b)

Figure 2: The horizontal and vertical position of VPP for different subjects at free speed. The height of the bars represents the mean of distance between VPPs and WBCoM for each subject in several trials. The error bar indicate variance of VPP's horizontal displacement. a) Vertical position of VPP in the WBCoM-centered coordinate frame, b) Horizontal position of VPP in the WBCoM-centered coordinate frame. * In this subject, the transition order of the legs is: LSS$-$ $>$DS$-$ $>$RSS.

between the left and right hip joint in the frontal plane, investigating the horizontal location of VPP with respect to CoM is also informative. according to Fig. 2b in the left single support phase (LSS), VPP is on the left side of WBCoM and in the right single support phase (RSS) VPP is located on the right side of WBCoM. In all trials except for subject 10, the stride starts with RSS. As shown in Fig. 2b, there is a relationship between transition order of the legs (from right to left or vice versa) and VPP's horizontal position, except for subject 5. for this subject, VPP is located above the WBCoM in double support phase.

4 Conclusions

In this study, VPP concept has been used to analyze lateral stability which had not been investigated before. The VPP is clearly observable in the coordinate systems that we chose. Unlike sagittal plane [2], we found that VPPs are mostly placed below the CoM in the frontal plane. The VPP below the CoM can be modeled as an inverted pendulum which is inherently unstable. Here, we explain how such a system with unstable sub-systems can lead to stable behavior (with the 3IP model shown in Fig. 3). We found that in the right single support (RSS), the VPP is located on the right side of CoM and in the left single support (LSS), the VPP is located on the left side of CoM. With the touch down of the left leg, VPP moves to the left side of the CoM. The initial horizontal speed of the CoM (to the left) is sufficient for the inverted pendulum in the double support phase (DS) to continue its leftward movement and to pass the vertical alignment. Then, the motion to the left speeds up until take-off of the right leg which switches the pivot point for the second time and results in LSS phase. This speed is not sufficient to pass vertical alignment of the inverted pendulum and it moves back and forth (left and right) to return to its LSS initiation position. The reverse motion in DS continues to reach the RSS phase and this loop holds during walking. When the left leg toes off, the VPP moves to the left side of the CoM. This study shows, using three inverted pendulum (3IP) with separated pivot points (Fig. 3a), can explain stability in the frontal plane. Fig. 3b presents another lateral balance model in which the VPP of DS is placed above CoM. The motion behavior predicted by this control strategy is less frequent in our experimental analyses. These models can describe lateral balance with a new presentation of VPP concept as a bioinspired method of balancing.



(a)

(b)

Figure 3: Proposed pendulum-based model of lateral posture control with sequential switching between a) inverted pendulum (IP) in the *3IP model* and b) combination of regular and inverted pendulum models.

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